Cold Regions Science and Technology 143 (2017) 93–104

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

# Predicting movement using internal deformation dynamics of a landslide in permafrost

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## ARTICLE INFO

*Keywords:*
Frozen debris lobe
Strain rate
Active layer
Brooks Range
Alaska
Permafrost

## ABSTRACT

Within the Brooks Range of Alaska, several frozen debris lobes (FDLs) – or slow-moving landslides in permafrost – are approaching critical infrastructure. FDL-A, the largest and closest of these features, was 32.3 m from the toe of the Dalton Highway as of October 2016. Here we present the analysis of nearly three years of data from a MEMS-based in-place inclinometer installed within FDL-A. Analysis of the strain within the active layer indicates that it is closely tied to air temperature and water, suggesting that cooling and/or draining the FDL may be effective mitigation techniques. Within the lobe body, strain rates are comparable to those measured within rock glaciers. Using the cyclical pattern and phase lag identified within the strain data, and surface movement rates 1) derived from historic imagery analysis and InSAR data, and 2) measured using a differential GPS system, we developed and vetted a predictive function for surface movement of FDL-A. The predictive function indicates that FDL-A moves at an average rate of 4.9 m $\mathrm{yr}^{-1}$, reaching a maximum velocity of 7.9 m $\mathrm{yr}^{-1}$ during the fall, and falling to 1.9 m $\mathrm{yr}^{-1}$ in the early spring. We hypothesize that the seasonal movement pattern is due to the infiltration of snow melt, and the subsequent reduction of effective stress within the shear zone. Using the predictive function and the measured October 2016 distance, we predict that FDL-A will reach the current Dalton Highway embankment during early 2023.

## 1. Introduction

Slope stability in cold regions is a growing concern, given potential permafrost degradation due to increased temperatures and precipitation (Seneviratne et al., 2012). Examples of increased instability due to degrading permafrost slopes are present throughout the Arctic, sub-Arctic, and mountainous regions, including: rock falls, debris flows, degrading rock glaciers, active layer detachment slides, and retrogressive thaw slumps (e.g., Balser et al., 2014; Deline et al., 2015; Huscroft et al., 2004; Lyle and Hutchison, 2006, Schoeneich et al., 2011; US News, 2012; US NPS, 2017). Frozen debris lobes (FDLs) – slow-moving landslides in permafrost – also demonstrate sensitivity to temperature and precipitation (Simpson et al., 2016). Nearly 160 FDLs have been identified in the central Brooks Range of Alaska, with at least 43 located within the transportation corridor containing the Dalton Highway and the Trans Alaska Pipeline System (TAPS; Fig. 1).

Although originally identified in the 1970s and 1980s in association with the construction of TAPS and related infrastructure (Brown and Kreig, 1983; Hamilton, 1978, 1979, 1981; Kreig and Reger, 1982), research on FDLs began in earnest in 2008 with preliminary investigations of four FDLs (Daanen et al., 2012), followed by a subsurface investigation of FDL-A in 2012 (Simpson et al., 2016). The area of interest (AOI) was expanded in 2013 to include monitoring of eight FDLs (Fig. 1b). These previous investigations consisted of drilling, sampling, and installation of instrumentation within FDL-A; sampling of soils and rocks for determination of geotechnical properties; refining geologic maps of the catchment bedrock; analysis of historic imagery to determine long-term movement rates; subsurface measurements of ground temperature and displacement; measurement of surface movement using a differential global positioning system (DGPS) unit; and remote sensing analysis using Light Detection and Ranging (LiDAR), Unmanned Aerial System (UAS), and Interferometric Synthetic Aperture Radar (InSAR) data (Darrow et al., 2016, 2017; Simpson et al., 2016; Gyswyt et al., 2017).

In this paper, we focus on horizontal displacement data from an in-place inclinometer installed within FDL-A (Fig. 1c) during the 2012 geotechnical investigation. In the literature, limited examples exist of the use of inclinometers to measure movement within permafrost or related features. Such examples range from measuring longitudinal strain in a temperate glacier in the Canadian Rocky Mountains (Savage

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http://dx.doi.org/10.1016/j.coldregions.2017.09.002
Received 27 April 2017; Received in revised form 28 July 2017; Accepted 5 September 2017

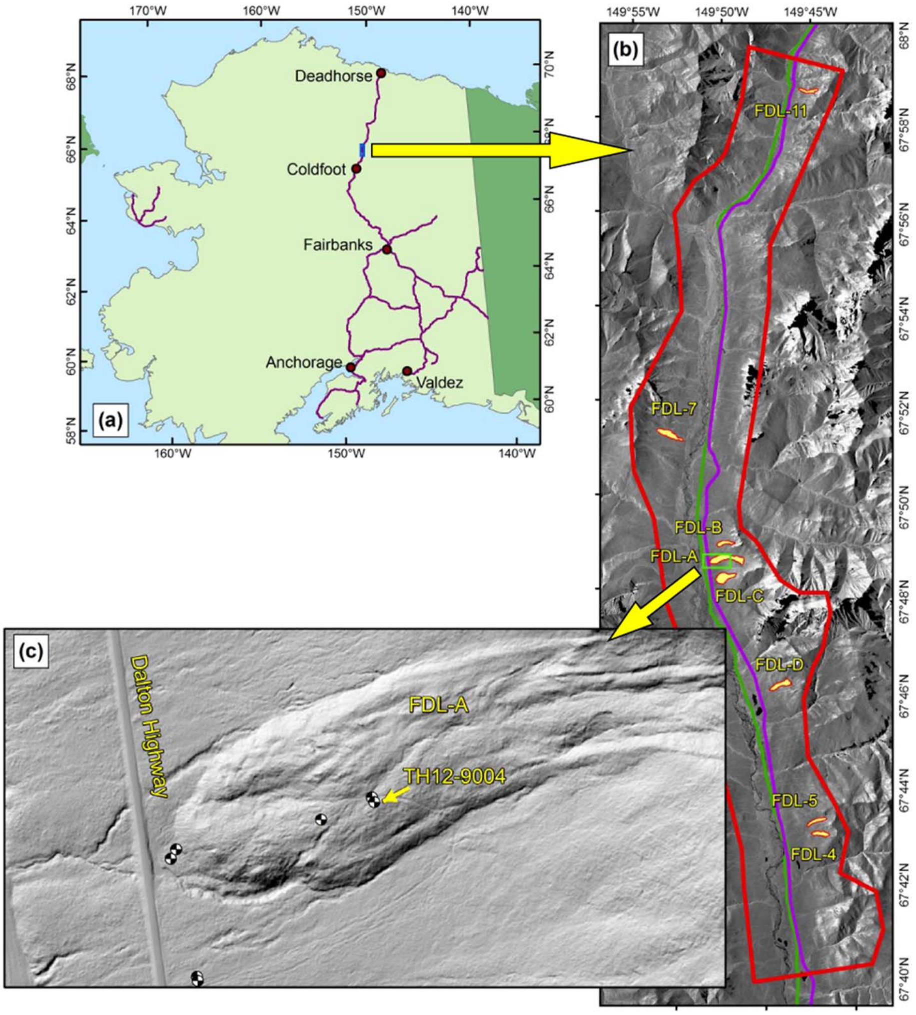

**Fig. 1.** Location map. (a) Field area (small blue rectangle) in relation to selected population centers in Alaska; (b) area of interest (AOI; shown as red polygon) and eight investigated FDLs; Dalton Highway is shown in purple and TAPS in green; (c) FDL-A (location shown as small green rectangle in (b)), with location of 2012 borings, and Dalton Highway. Base map data are from ASGDC, 2014, GINA, 2001, and 2015 LiDAR (unpublished). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and Paterson, 1963) to measuring creep of a massive ice body near Tuktoyaktuk, N.W.T., Canada (Foriero et al., 1998). Several researchers used inclinometers to measure permafrost creep and/or solifluction (Bennett and French, 1991; Savigny and Morgenstern, 1986a, 1986b; Wang and French, 1995), and Gischig et al. (2011) used manual and in-place inclinometers to measure annual and seasonal deformations within bedrock. Arenson et al. (2016) provide a summary of ground deformation monitoring within permafrost environments.

The studies most relevant to the FDL research are those that employed inclinometers within rock glaciers (Arenson, 2002; Arenson et al., 2002; Buchli et al., 2013; Ikeda et al., 2008; Konrad, 2001), with results indicating temperature-dependent movement. The analysis of FDL-A by Simpson et al. (2016) alluded to a temperature-dependent relationship of its internal movement. In order to explore this relationship further, here we present nearly three years of displacement and ground temperature data, and analysis of strain in the active layer and at depth within the lobe. We integrate these results with those derived from DGPS measurements of the lobe surface and remote sensing to develop a predictive function for FDL-A's rate of movement, and using the function we provide a refined estimate for when FDL-A will impact the current Dalton Highway alignment.

### 1.1. Study site

The AOI is located in the south-central Brooks Range, approximately 70 km north of Coldfoot, Alaska (Fig. 1a). The eight investigated FDLs within the AOI have an average size of ~15 ha. They are composed of silty sand with gravel to silty gravel with sand (SM and GM, respectively, using the Unified Soil Classification System; Simpson et al., 2016). FDLs are composed of ice-poor soil (i.e., containing no excess ice with volumetric moisture contents less than the calculated soil porosity; Darrow et al., 2016). They typically originate in cirque-like catchments, which consist of highly fractured and foliated, very low to medium strength bedrock that contributes to FDL formation (Darrow et al., 2016). Once they leave their catchments, FDLs have elongated, tongue-like morphologies.

FDL-A is the largest of the investigated FDLs, with an area of 28.6 ha. It is 1378-m long and 241-m wide, with a thickness varying from approximately 20 m at its toe to 26 m near its center, and becoming thinner towards its catchment. It originates at an elevation of approximately 860 m asl (Fig. 2). Leaving the catchment, it moves down a 5° slope to a final elevation of 540 m asl; this elevation is based on its location in 2015 as determined from LiDAR data. As of October 2016, FDL-A was 32.3 m from the toe of the Dalton Highway embankment.

### 1.2. Summary of 2012 investigation and instrumentation installation

In September 2012 and working with the Alaska Department of Transportation and Public Facilities (ADOT & PF), we conducted a geotechnical site investigation of FDL-A, drilling eight borings (3.0-m to 30.48-m deep) within and adjacent to the lobe. The key boring on which we focus in this paper is TH12-9004 (indicated in Fig. 1c), which reached a depth of 30.48 m below the ground surface (bgs). The boring